NEL / REPORT 1374

PHOTO ANALYSIS OF SEA FLOOR MICRORELIEF

On the basis of over 700 NEL sea floor photographs, numerical microroughness ratings have been predicted for normal bottom environments, and zones of equal microroughness mapped for large portions of Pacific and adjacent ocean areas.

C. J. Shipek • Research Report • 26 April 1966

U. S. NAVY ELECTRONICS LABORATORY, SAN DIEGO, CALIFORNIA

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PROBLEM

Determine and study those characteristics of the sea floor that affect the propagation of acoustic energy in the sea. Specifically, investigate the character, magnitude, and distribution of sea floor microrelief and its superposition on intermediate and major underwater topographic features.

RESULTS

1. More than 700 NEL sea floor photographs, obtained over the past ten years, in a wide variety of environments, have been analyzed. The bottom microrelief has been related to the major agencies responsible for its formation and, on this basis, five predominating types of microrelief have been defined.

2. General ranges in the vertical height and horizontal extent of the microrelief have been determined for the upper exposed surfaces of 39 intermediate underwater features that are, in turn, related to 12 major features or provinces.

3. Microroughness ratings, on a numerical scale of 1 through 5, are predicted for normal bottom environments. These ratings should prove useful in acoustic problems.

4. Isoroughness zones have been mapped for large portions of the Pacific and adjacent ocean areas.

RECOMMENDATIONS

1. Continue combined photographic, sediment, water-sampling, water-current, and temperature studies at ocean stations to improve the reliability of microroughness predictions for the sea floor.

2. Construct microprofiles of the sea floor covering vertical, horizontal, and slope measurements of microrelief for correlation analyses. The principles of photogrammetry should be applied if stereo cameras are utilized to obtain the needed data.

3. Encourage the study of micro and intermediate relief as an aid to the future operation of submersibles and tracked vehicles on the sea floor.

4. Encourage further use of portable, subbottom, acoustic profiling methods to help establish the relationships of microrelief at the sediment-water interface to deeper substrata features.

ADMINISTRATIVE INFORMATION

Field work for this project has extended over the past 10 years on an intermittent basis. This report was prepared under BUSHIPS Problem SR 104 03 01, Task 0539 (NEL Problem L4-1 (now L40161)). It was approved for publication on 26 April 1966.

Many scientists and crew members on numerous oceanographic cruises helped the author lower cameras, collect samples, and process film; they are too numerous to be named here. Special thanks are due to R. E. Boyce for the preparation of photographic grid scales and help in the analysis of bottom photographs; to D. Muerdter for mathematical assistance; and G. L. Prible, D. Bachman, and Mrs. Renee Forsyth for the preparation of maps and illustrations.

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INTRODUCTION

The purpose of this report is to describe photographic samplings of very small bottom-relief features found at different depths in the ocean and in different environments; and to show how photographic and related information from the surfaces of intermediate topographic features can be interpreted to predict the general nature of the microrelief and project microrelief characteristics from area to area. Approximately 700 bottom photographs of the surfaces of selected underwater features in the Pacific, Indian, and Arctic Oceans, and in the Gulf of California, have made this study and analysis possible.

HISTORICAL BACKGROUND

Early mariners probed the sea bottom in shallow nearshore waters and brought up samples of sand, clay, and rock. Their major interest was in making safe passages across the oceans and in and out of harbors and channels. The shortness of their sounding lines prevented them from reaching the deeper sea floor surfaces. Consequently little was learned about the detailed microcharacter of the deep sea floor. On the basis of meager knowledge and scattered samples, many thought of the sea floor as an extremely flat, monotonous plain composed of a soft, clayey upper surface that blended gradually upward into seawater. In recent times, sonic depth finders, deep-sea cameras, modern sampling equipment, acoustic probes, and manned diving submersibles have revealed the structure and character of what is referred to as microrelief at the sea floor.

Major underwater topographic relief features have now been located and mapped. Distinct provinces encompassing similar features have been recognized and delineated.[1,2] Intermediate bottom features are now being studied to make our knowledge of the sea floor more comprehensive and to provide a basis for the examination of microroughness and internal structures.[3] It has been shown, for example, that abyssal hills cover 80 to 85 percent of the Pacific floor alone while, in other areas, bottom environments vary from smooth plains to steep eroded escarpments, mountain ranges, and fracture zones of irregular roughness.[4]

For many years the very small vertical relief on the sea floor was not thought to be significant to mankind. Recent advances in methods of propagating and receiving underwater sound signals, however, have shown that the roughness formed by natural chemical, physical, and biological forces at the sea floor has sufficient height and extent to affect the reflection and scattering of certain sound frequencies therefrom. Thus, Urick[5] made backscattering studies of the bottom in 1954 with a tiltable transducer at several locations in a harbor on the East Coast.

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[1]Superscript numbers denote references in the list at the end of this report.

His results suggested that backscattering of sound from a natural bottom is due more to its roughness than to the sedimentary particles that make it up, and that at normal incidence the bottom is sufficiently rough so that little sound is returned by specular reflection. The increase in scattering for sand-rock bottom seemed to be due to the greater roughness. Again, in 1960, Urick[6] utilized two transducers to study side scattering over a uniform bottom. The results indicated that isotropic bottom scattering may be safely assumed in applications utilizing separated transmitting and receiving transducers at kilocycle frequencies. As examples of sea scatterers of sound, Urick listed marine life, the air bubbles existing near the sea surface in bad weather, and the roughnesses of the sea floor. The latter are known to be the dominant sound scatterers in shallow water when the bottom is hard and when downward refraction exists.

Mackenzie[7] made bottom reverberation measurements with 530 and 1030 c/s omnidirectional sound sources in 2100-fathom water near San Diego. An analysis of nonspecular reflections to obtain a scattering constant for the bottom revealed that, for clays, muds, or fine-grained sands, there appears to be no significant frequency dependence over a range of seven octaves. Mackenzie[8] stated that, for frequencies from 200 to 3000 c/s in long-range shallow-water propagation, bottom reverberation is probably the only important type of reverberation. He pointed out that accurate close-range reverberation studies over different bottoms and especially at lower frequencies are needed for grazing angles from 1° to 10°, and he noted that reverberation strength is more significant than reverberation level.

In discussing the theory of sound reflection from flat and uniform fluid bottoms, Mackenzie[9] stated that more measurements should be made of the bottom reflection properties, especially for grazing angles of incidence from zero to 30° where the results are more critically dependent on the bottom properties.

Lieberman[10] measured the reflection coefficient of the ocean bottom for supersonic sound (24 kc/s) at grazing

incidence, and found that it depended not only on the median size of the particles making up the bottom, but also on the sorting of the particles and on the bottom topography. Working at 17 stations near Woods Hole, Massachusetts, he obtained the following *in situ* reflection coefficients for five gradations of materials at the sediment-water interface:

mud	0 to 0.20
mud-sand	0.20 to 0.40
sand-mud	0.40 to 0.60
sand	0.40 to 0.85
stony	0.50 to 0.85

It can be seen that sand and stony bottoms have the best reflecting ability. Lieberman stated that an exact treatment of the reflection from an irregular surface may be given only if the geometry of the surface is completely specified.

DEFINITION OF MICRORELIEF

Earth forces and water movements have created great trenches, rises, mountain ranges, seamounts, scarps, and other significant relief features in deep-sea environments. The sediments that are continually forming at the sea floor are also not without relief, even though this relief is of very small magnitude compared to that of the larger features.

The term "underwater microrelief" usually refers to those very small features not ordinarily detected by modern echo-sounders. Laughton[11] used the term "microtopography" and defined it as referring to those features of the sea floor that can be visually observed in the scale range of 50 meters to 1 mm. (He regarded 50 meters as approximately the limit of visibility in the clearest of oceanic water.) Carsola[12] defined microrelief on the arctic sea floor as consisting of the smallest features that can be resolved at depths between 0 and 200 fathoms (366 meters) with the NMC and NMC-2

echo-sounders. He added that the pits and mounds of the microrelief areas are in places 60 ft (18+ meters) from bottom of depression to top of rise, but usually only 6 to 30 ft (1.8 to 9.1 meters).

The author of this report has defined microrelief[13] as the very small surficial topographic features that are superimposed on both major and intermediate relief and are distinguishable by examination of bottom photographs (fig. 1). Vertical heights are measured in centimeters and meters, and lengths in meters and occasionally tens of meters. Major underwater relief, at the other extreme, encompasses the larger earth features such as deep trenches, high plateaus, rises, and mountain ranges. Intermediate relief consists of the smaller underwater topographic features such as low hills, valleys, banks, small basins, gullies, and island slopes that may be parts of major features, but are still too large to be photographed in their entirety with present-day underwater cameras. Microrelief, as defined by the author, covers 100 percent of the sea floor, whereas intermediate and major relief features are localized and discontinuous.

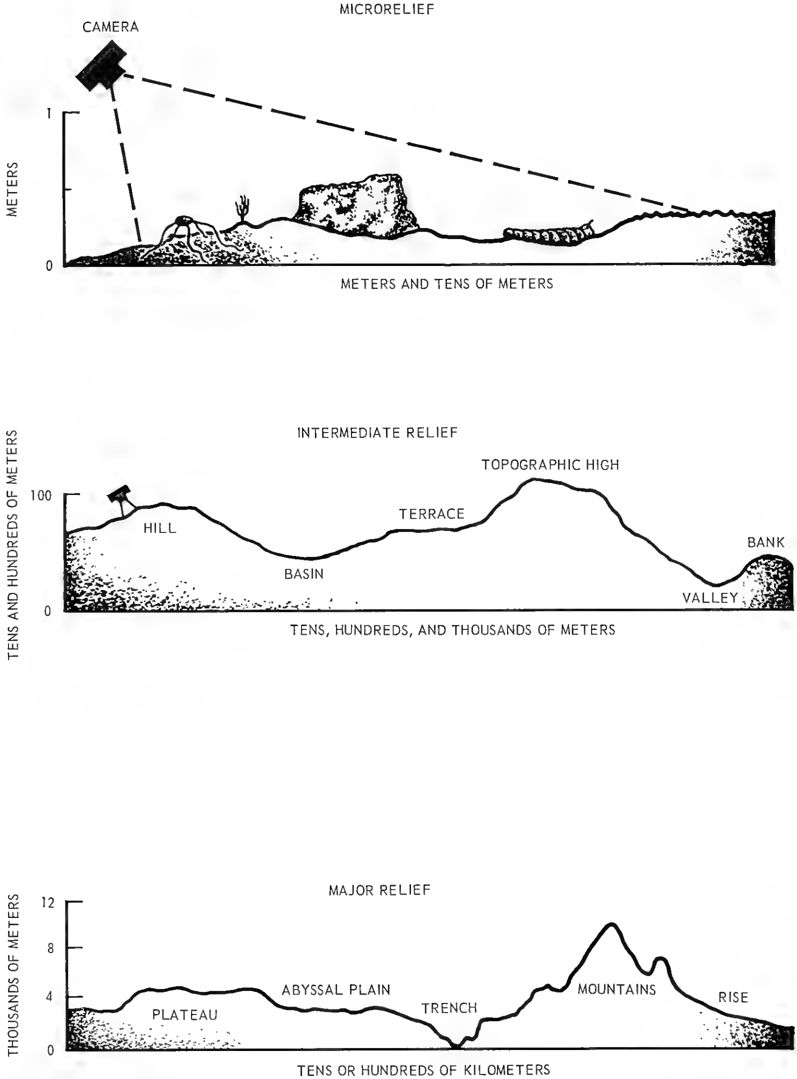

Figure 1. Sea floor topographic relief.

SUMMARY OF MICRORELIEF PHOTOGRAPHIC DATA

Various parts of the surfaces of 39 intermediate topographic features of the Pacific Ocean, Indian Ocean, Arctic Ocean, and attached water bodies were sampled photographically. These intermediate features were parts of 12 major topographic features or provinces. (The photographic techniques and cameras used are described in the next section.) Figure 2 is a world map showing the locations of the NEL deep-sea camera stations occupied for this purpose, and their relation to the major underwater topographic features.

These camera stations were not all preselected to obtain the greatest number of similar or dissimilar sea floor characteristics. Many photographs were taken from oceanographic vessels moving along tracks designated for other scientific programs. Available vessel time along these routes, however, made it possible to obtain photo samplings of a wide variety of sea floor features.

Table 1 is an overall summary of the photographic data. It relates the 12 major features, the 39 intermediate features, and the associated microrelief as found by random sampling in the areas surveyed. It also gives the heights, lengths, and widths of the visible targets at the sediment-water interface, and the dimensions of free chemical and biological specimens. Although the latter are not permanent parts of the relief, they are included here because of their significance in acoustics. Many crest lengths of physically formed ripples were not determinable from the small-area bottom photographs.

Table 2, like table 1, relates the major and intermediate topographic features and the associated microrelief, but classifies the microrelief into five types based on the five principal agencies responsible for its formation.

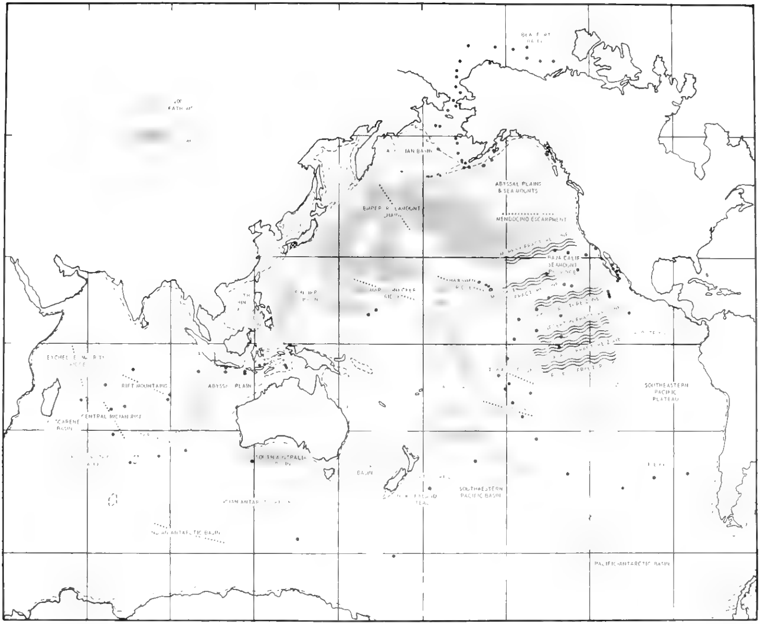

Figure 2. Map showing NEL sea floor camera stations and underwater topographic features

TABLE 1. UNDERWATER TOPOGRAPHIC RELATIONSHIPS AND PHOTO ANALYSIS OF SEA FLOOR MICRORELIEF

MAJOR TOPOGRAPHIC FEATURE	INTERMEDIATE TOPOGRAPHIC FEATURE	BOTTOM SEDIMENT	PHOTO DEPTHS (meters)	MICRORELIEF (FROM PHOTO INTERPRETATION) TYPE	SIZE (cm) Width x Length	HEIGHT (cm)	COVERAGE OF PHOTO (percent)	NUMBER OF BOTTOM PHOTOS
CONTINENTAL TERRACE	BANK	Sandy silt Pebbles, cobbles Debris	495 to 1154	Outcrops	27 x 28	1[illegible]	35	10
				Brittle stars, sea urchins, sponges	8 x 8	3	20	30
				Churning	11 x 25	7	—	30
	BASIN	Silty clay Excrement	600 to 1800	Worms, brittle stars, starfish, sea pens, sea cucumbers, crinoids	4 x 7	3	1	52
				Chemical reduction	—	1	20	10
				Churning	8 x 15	4	—	55
	CANYON OUTER	Silt, fine sand Debris	620 to 1100	Brittle stars, sea pens, crustaceans, worms, gastropods, fish	8 x 9	3	7	27
				Churning	12 x 23	9	—	27
	ISLAND SHELF	Silty fine sand Coarse material Debris	25 to 100	Rock fragments, animal shells, worms,	33 x 33	4	1	5
				sea urchins, pelecypods	3 x 8	16	19	26
				Churning	8 x 12	3	—	26
				Ripple marks	— x 30	2	2	3
	CONTINENTAL SLOPE	Silty clay	158 to 638	Brittle stars, gastropods, sea pens, starfish	16 x 17	3	20	7
				Churning	6 x 8	4	—	[illegible]
	SILL	Silty clay	1134	Brittle stars, animal shells, sea pens	4 x 5	2	2	8
				Churning	5 x 9	4	—	6
	SADDLE	Silty clay	542 to 900	Brittle stars	4 x 4	2	13	14
				Churning	4 x 8	2	—	13
	TROUGH	Silty clay Debris	340 to 1080	Outcrops or rock fragments	10 x 16	6	32	13
				Brittle stars, sea cucumbers, worms, sea urchins, crinoids, crustaceans	8 x 10	3	21	27
				Churning	5 x 8	3	—	26
	VALLEY	Silty clay Debris	491 to 5[illegible]2	Sea urchins, sea cucumbers, worms, sea pens, fish	5 x 7	3	3	16
				Churning-plow trails	5 x 52	3	—	16
	RIFT VALLEY	Silty clay and sand Excrement	2025 to [illegible]360	Brittle stars, sea urchins, sea pens, starfish	3 x 13	6	3	11
				Churning-pits	7 x [illegible]	4	—	11
RIDGE	BASIN	Clay Debris	4080	Manganese nodules	2 x 2	1	5	2
				Sea cucumbers, worms	5 x 1	2	1	1
				Churning	1 x 3	5	—	1
	GENTLE RELIEF 275 Meter Hole	Calcareous ooze Debris	3180 and 3520	Sea urchin, worms, sponge	4 x 4	10	1	3
				Churning-plow trails	3 x 2[illegible]	4	—	4
				Ripple marks-faint	—	—	—	2
	ISLAND SHELF	Silt Debris	497	Outcrops or boulders	12 x 1[illegible]	8	63	[illegible]
				Sea pens, worms, sponges, brittle stars	[illegible] x [illegible]	3	24	1[illegible]
				Churning-pits, mounds	20 x 2[illegible]	3	[illegible]	12
				Ripple marks	— x 25	4	—	2
	SEAMOUNT SURFACE	Calcareous ooze	1320	Manganese nodule fragments	1 x 1	1	1[illegible]	[illegible]
				Ripple marks, sorting	16 x [illegible]	5	90	2
GULF OF CALIFORNIA	BASIN	Silty clay and pebbles Debris	610 to [illegible]	Outcrops, boulders	20 x 2[illegible]	35	1	15
				Corals, starfish, sponges, worms, fish, brittle stars, sea pens	4 x 6	7	12	44
				Churning	4 x 16	[illegible]	—	3[illegible]
	CANYON INNER	Coarse sand and silt Debris	[illegible]32 to 1866	Outcrops	22 x 34	48	25	8
				Brittle stars, fish, worms, sponges	13 x 13	[illegible]	10	18
				Churning	—	14	—	13
				Ripple marks	— x 20	2	60	1
	ISLAND SHELF	Sand and silty clay Debris	[illegible]7 to 170	Outcrops, boulders	3 x 3	4	1[illegible]	[illegible]
				Brittle stars, sea pens, animal shells, sea urchins, corals, worms	4 x [illegible]	16	[illegible]	20
				Churning	[illegible] x 9	2	—	3
	SMALL LOCAL RIDGE	Coarse gravel Manganese grains Debris	[illegible]20	Outcrop, boulders, rock fragments	13 x 15	12	80	1[illegible]
				Brittle stars, sea urchins	[illegible] x 10	[illegible]	5	11

TABLE I (CONTINUED)

MAJOR TOPOGRAPHIC FEATURE	INTERMEDIATE TOPOGRAPHIC FEATURE	BOTTOM SEDIMENT	PHOTO DEPTHS (meters)	MICRORELIEF FROM PHOTO INTERPRETATION: TYPE	SIZE (cm) Width x Length	HEIGHT (cm)	COVERAGE OF PHOTO (percent)	NUMBER OF BOTTOM PHOTOS
FRACTURE ZONE EAST PACIFIC	BASIN	Fine clay Coarse particles	5180	Manganese nodules Sea cucumbers or excrement Churning	3 x 4 2 x 5 1 x 3	3 2 2	56 1 –	7 1 [illegible]
	IRREGULAR HILLS 180 Meter Relief	Fine clay Coarse particles	4990	Manganese nodules Sea urchins, sea cucumbers or excrement Churning	2 x 4 32 x 32 2 x 3	2 15 2	5 1 –	6 1 7
	GENTLE TOPOGRAPHY	Clay Detrius	5400	Manganese nodules Sponge, worms Churning	2 x 2 2 x 2 2 x 10	2 2 2	1 1 –	3 2 8
	IRREGULAR TOPOGRAPHY	Clay	4408	Manganese nodules Churning	3 x 3 1 x 1	2.5 1	20 –	2 2
ABYSSAL PLAIN	GENTLE TOPOGRAPHY	Calcareous ooze Clay	3290 to 5100	Outcrop, boulders, manganese oxide crusts Coral, sea cucumbers, sponges, worms Churning Ripple marks	43 x 57 2 x 2 5 x 12 120 x 11	31 2 4 2	20 3 – 70	5 16 18 8
RISE EAST PACIFIC	ISLAND SLOPE Clipperton Is	Calcareous debris Shells	274 to 437	Outcrop-volcanic rock and coral Tube worms Churning	10 x 100 5 x 5 10 x 12	19 5 3	26 3 –	3 [illegible] 5
	IRREGULAR TOPOGRAPHY	Calcareous ooze Clay	3477	Manganese nodules Boulders Sea pens, sea cucumbers, worms Churning	16 x 21 3 x 5 5 x 13	11 1 3	31 1 –	67 33 65
RISE CENTRAL INDIAN	ISLAND SLOPE	Volcanic sand Cobbles and pebbles Coral debris	448	Outcrops, volcanic, boulders Sea urchins, sea cucumbers, coral, fish Churning Ripple marks	5 x 8 5 x 7 2 x 3 – x 10	5 4 2 1	24 10 – –	15 17 15 9
DEEP SEA BASIN	LOW HILLS	Clay	4254 and 4940	Manganese nodules Brittle stars, coral Churning	7 x 8 3 x 3 3 x 5	6 [illegible] 3	10 5 –	1 5 [illegible]
	GENTLE TOPOGRAPHY	Clay	2094 to 5330	Manganese nodules Sea anemone Churning-mounds	3 x 3 15 x 15 4 x 1[illegible]	2 5 2	75 –	4[illegible] 1 45
TRENCH	GENTLE TOPOGRAPHY	Foraminiferal sand	6580	Sponges, sea anemones, coral Churning	10 x 10 4 x 15	10 5	1 –	1 1
	LOCAL RIDGE	Foraminiferal sand Gravel Coarse material	1500	Crusting-chemical Outcrop, boulders Churning trails, mounds, pits Ripple marks	80 x 120 40 x 70 5 x 200 7 x 100	1 5 2 2	70 26 – 7[illegible]	[illegible] 11 5 3
	FLAT TOPOGRAPHY	Silty clay	500[illegible]	Worms Churning	2 x 3 3 x 4	2 2	10 –	15 15
RIFT MOUNTAINS	TOPOGRAPHIC HIGH	Globigerina ooze	[illegible]940	Manganese nodules and crusting Outcrop Churning Ripple marks	8 x 8 2 x 3 150 x 90	[illegible] 2 1[illegible]	100 – 100	2 1 1
	INTERMOUNTAIN VALLEY	Clay	1760	Worms, sea anemone, gastropods Sediment slumping-sea cucumbers Churning-mounds, pits	2 x 2 8 x 30 6 x 18	3 12 4	5 40 –	17 1 18
SEAMOUNT PROVINCE	ABYSSAL HILLS	Siliceous ooze	4140 to 471	Manganese nodules Sponges, worms, sea urchins Churning	4 x 7 3 x 3 5 x 7	3 1 2	[illegible] 5 –	1 [illegible] [illegible]
	SEAMOUNT SURFACE	Calcareous sand Debris	1460 to [illegible]015	Manganese nodules and fragments Chemical crusting Ripple marks	4 x 5 – 100 x 18	[illegible] 1 1	18 50 80	30 11 31
	IRREGULAR TOPOGRAPHY	Clay	5520	Pavement slabs manganese crusting	15 x 17	5	4	1[illegible]
BEAUFORT SEA	SLOPE	Clay Debris Pebbles scattered	549 to [illegible]423	Brittle stars Churning-tracks, trails	1[illegible] x 15 [illegible] x 15	2 2	2 –	5 16
	SEA VALLEY	Clay Debris Pebbles scattered	6[illegible]4 to 18[illegible]	Fan worms, brittle stars, holothurian Churning	17 x 18 2 x 7	3 2	5 –	16 10
	SMOOTH TOPOGRAPHY	Silty clay Debris	55[illegible]8 and [illegible]	Sea pen Churning-trails	1 x 1 2 x 30	8 1	[illegible] –	1 [illegible]

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TABLE 2. DISTRIBUTION AND GENERAL RELATIONSHIPS OF UNDERWATER TOPOGRAPHIC RELIEF

MAJOR RELIEF	INTERMEDIATE RELIEF	MICRORELIEF				
		OUT-CROPS	CHEMICAL DISTURB.	BENTHONIC ANIMALS	BIOLOG. DISTURB.	PHYSICAL DISTURB.
CONTINENTAL TERRACE	BANK					
	BASIN					
	CANYON					
	ISLAND SHELF					
	CONTINENTAL SLOPE					
	SILL					
	SADDLE					
	TROUGH					
	VALLEY					
	RIFT VALLEY					
RIDGE	BASIN					
	GENTLE RELIEF					
	ISLAND SHELF					
	SEAMOUNT SURFACE					
GULF OF CALIF.	BASIN					
	CANYON					
	ISLAND SHELF					
	SMALL LOCAL RIDGE					
FRACTURE ZONE	BASIN					
	IRREGULAR HILLS					
	GENTLE TOPOG.					
	IRREG. TOPOG.					
ABYS. PLAIN	GENTLE TOPOG.					
EAST PAC. RISE	ISLAND SLOPE					
	LOW HILLS					
CNT. IND. RISE	ISLAND SLOPE					
DEEP SEA BASIN	LOW HILLS					
	GENTLE TOPOG.					
TRENCH	GENTLE TOPOG.					
	LOCAL RIDGE					
	FLAT TOPOG.					
RIFT MTS.	TOPOG. HIGH					
	INTERMOUNTAIN VALLEY					
SEAMOUNT PROVINCE	ABYSSAL HILLS					
	SEAMOUNT SURFACE					
	IRREG. TOPOG.					
BEAUFORT SEA	SLOPE					
	SEA VALLEY					
	SMOOTH TOPOGRAPHY					

THE CAMERAS AND TECHNIQUES USED

The type of form used for recording the results of the examination of each photograph is shown in figure 3A. Figure 3B shows the back of this form on which was listed the properties of any water, sediment, or animal sample taken in the area.

Three types of deep-sea camera systems were employed for the collection of the bottom photographs. Type I (fig. 4) has a tilted semiwide-angle lens of 30 mm focal length, and uses 35 mm film and a repeating electronic flash light mounted in an upright frame. A bottom contact switch activates the light and causes the film to advance each time a lowered weight touches the sea floor. All photos taken with this apparatus were low obliques (30° from the vertical) at a preset target distance of 6 feet underwater. Figure 4 also shows the grid scale used for making measurements on the photos taken with this camera system.

Type II camera (fig. 5) has a sled-type frame supporting a 35 mm camera and a flash unit which can rotate about a common axis to give vertical or oblique photos. Normally the camera angle was set close to the horizontal (15° from the horizontal) to permit greater bottom coverage even though the photo scale was more distorted. This camera was usually lowered to a preselected target distance and then allowed to drift over the sea floor using sonar to control the height above the bottom. Photographs were taken automatically at preset time intervals. Excessive heave and roll of the lowering vessel caused unwanted deviations from acceptable depths of focus. Figure 5 shows the optics and grid overlay for photo measurements.

The Type III camera is a 35 mm Edgerton, Germeshausen, and Grier stereo underwater system. Photo pairs were taken with the camera axes oriented vertically and set at a prefixed separation. Figure 6 shows the optics and field coverage for this system.

The grids for the three camera systems are constructed of clear plastic. They were applied as overlays in examining the bottom photos, and established scale for

A. FRONT OF CARD

PHOTO ANALYSIS

Station ____ Cruise ____ Vessel ____ Photographer ____ Date ____
Photo No. ____ Total ____ Depth-M Uncorr. ____ to ____ Lat. ____
Vault No. ____ Camera Type ____ Depth-M Corr. ____ to ____ Long. ____
Area ____ Major Topog. ____ Intermediate Topog. ____
Sediment Type ____ Color ____ Sample ____ Slope < ____

PHYSICAL DISTURBANCES: Ripple Marks ____ Pattern ____ Shape ____ Ht ____ L ____ Coverage ____
Scour ____ Slumping ____ Slipping ____ Banking ____ Capping ____ Sorting ____
Current Velocity ____ Direction ____ Transparency ____ Water Sample ____
Bending of fauna and other ____ Orientation of fauna ____

ORGANIC PRODUCTIVITY: Benthic ____ Pelagic ____ Ht ____ L and W ____ Coverage ____
Range H ____ L ____ W ____

ORGANIC DISTURBANCES: Debris ____ Tracks ____ Trails ____ Tubes ____ Pits ____ Mounds ____
Excrement ____ Churning ____ Scratches ____ Old ____ New ____ Other ____
Average H ____ L ____ W ____ Range H ____ L ____ W ____ Coverage ____

CHEMICAL DISTURBANCES: Nodules ____ Crusts ____ Slabs ____ Fragments ____ Other ____
Composition ____ Hardness ____ Color ____ Coverage ____

ROCKS: Bedrock ____ Boulders ____ Cobbles ____ Pebbles ____ Fragments ____
Average H ____ L ____ W ____ Range H ____ L ____ W ____
Strike ____ Dip ____ Color ____ Hardness ____ Sample ____ Coverage ____

Remarks:

Single ____ Stereo ____ % overlap ____ Camera Elev. ____ Scale: 1 cm = ____ Contour Int. ____

B. BACK OF CARD

LABORATORY ANALYSIS

I. Sample Analysis
- A. Sediment
  1. Type ____
  2. Med. Diam Gr. (mm) ____
  3. % sand ____
     % silt ____
     % clay
  4. Density, sat. gr/cc ____
  5. Porosity ____ %
  6. Bulk Density Mineral, gr/cc ____
  7. Shear Strength, gr/cm^2 ____
  8. Sound Speed, m/sec. ____
  9. Attenuation, dB/m ____
  10. Other Properties or Constituents:
  11. Rate of Accumulation ____
      a. Method ____
- B. Bottom Water Analysis
  1. Temp., deg. C. ____
  2. Salinity, ppt. ____ Sigma-T ____
     a. Bottle No. ____ Sp. Vol. An. ____
  3. Pressure, kg/cm^2 ____ Density ____
  4. Sound Speed ____
     a. Ratio: $\frac{\text{sound speed sed.}}{\text{sound speed water}}$ ____
- C. Summary of Microrelief and causes:

Figure 3. Photo and laboratory analysis card.

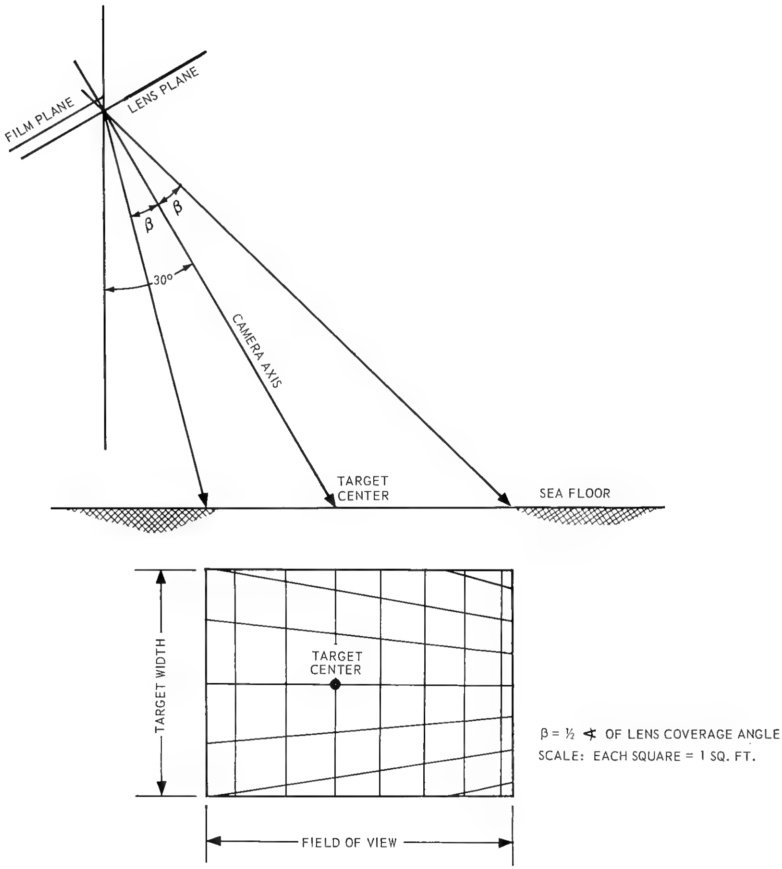


Figure 4. Camera, Type I, low oblique photographic coverage of sea floor.

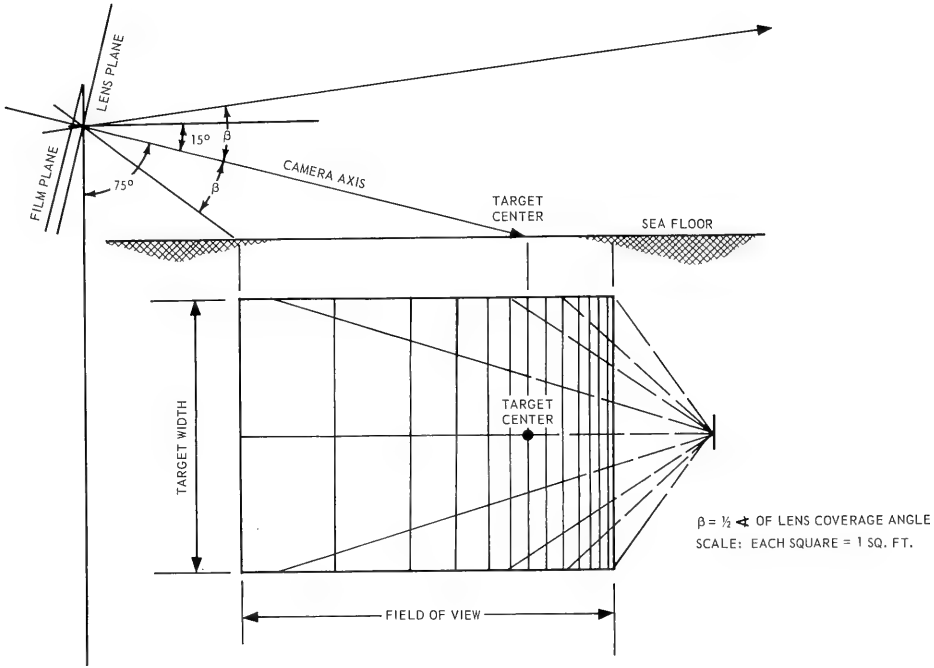


Figure 5. Camera, Type II, high oblique photographic coverage of the sea floor.

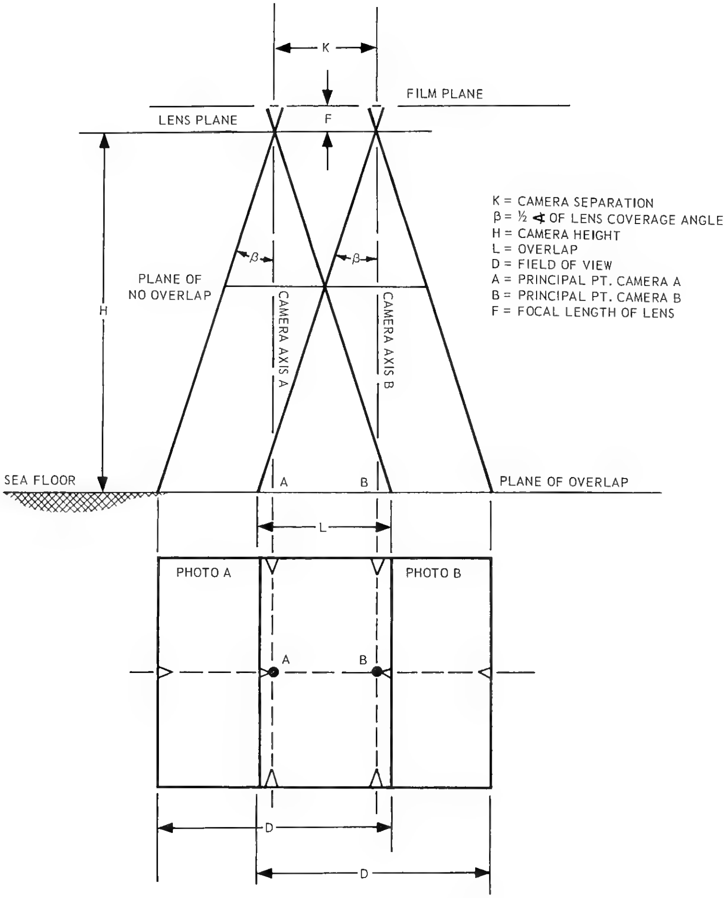


Figure 6. Camera, Type III, vertical stereophotographic coverage of the sea floor.

all parts of each photo. With the proper grid, measurements of ripple marks, benthonic organisms, nodules, rocks, and other relief features were made on each photo when such were distinguishable. Composition of sediment samples and the water clarity were correlated with photo interpretation and measurements whenever possible. With all three camera systems, target distance seldom exceeded 12 feet (3.7 meters).

INTERPRETATION OF BOTTOM PHOTOGRAPHS

Value and Limitations of Bottom Photography

While the human eye has the ability to see and interpret, it is unreliable and it cannot retain accurate images for future use. In contrast to the eye, the camera faithfully records everything in its field of view. The image is substantially permanent, and variations can occur only when the photographic prints are being measured and interpreted. As a consequence, the development and application of the underwater camera have shed new light on the nature of the sediment-water interface.

Fortunately, many techniques used for measurement and interpretation in engineering photography can be, and are being, used in the study of underwater microrelief. Photography as applied to underwater surficial relief does not differ basically from subaerial photography, but the submarine environment is much more difficult to work in. Because of refraction, the angular coverage of the usual lens is restricted in water, and corrections must be made to get normal, undistorted views. Seawater also scatters and absorbs light much more than does dry, clear air. Except in the clearest of deep oceanic waters, target distances for underwater photography are limited to less than 12 feet (3.7 meters) for maximum resolution and detail. Photo coverage is thereby confined to relatively small areas. Electronic flash at 5000° Kelvin temperature gives the greatest light penetration under water.

In the study of the sea bottom, considerable application is being made of stereophotography, for which vertical camera axes are best. Microrelief viewed from directly above is in true plan view, but side detail is obscured. Conversely, when viewed from the side, the relief is clear but the plan view is highly distorted. For this reason oblique photography is used mainly for rapid exploratory work when side views of low relief features are desired and measurements are of secondary importance. When measurements of vertical height are the primary objective, modern methods of photogrammetry are being widely used.[14]

Methods Used in the Interpretation of the Photographs

The vastness of the oceans prohibits complete photographic and sediment sampling of the bottom surface with present-day oceanographic equipment. We can, however, build up composite pictures of local and regional bottom environments from collections of isolated camera samplings and associated information, such as sediment grain size, bottom currents, composition, nearness to land, topographic barriers, and availability of food supplies to benthonic organisms.

A complication in the study and interpretation of microrelief is that its structure is far from permanent. As Crozier has pointed out,[15] very considerable sediment turnover goes on over relatively short periods of time. In the shallow waters around Bermuda, in an area of 1.7 square miles, he found that 500 to 1000 tons of sand passed through holothurians (sea cucumbers) annually. This represents a layer of sediment about 1 centimeter thick every 100 years, and sediments have been forming for millions of years.

To overcome the difficulties in deriving patterns of origin and change on the sea floor, investigators use many and varied techniques of photo interpretation. Some of the more important are discussed in this section.

Photographic contrast has been found to be an effective means of detecting and describing visible targets, and of relating them to one another. Sharpness of definition is required in aerial photographs, but is even more important

underwater where suspended matter tends to obliterate the sharp edges of all targets more than a few meters from the camera. Sharpness of definition depends on such factors as lens quality, water transparency, exposure and target distance, type of film, quality of look-through port, and film processing. Since contrast is often poor in bottom photographs, it is necessary to apply indirect methods to decipher unknown and obscure markings. Shadow effects are used extensively for this purpose.

A knowledge of the agencies that create the microrelief can help in photo interpretation. For example, scratches, tracks, grooves, trails, impressions, pits, mounds, and holes can normally be related to some form of benthonic organism if enough photos of an area are examined. Obtaining actual specimens makes such identification easier and more reliable. Organisms in shallow environments sometimes can be viewed directly while creating their peculiar marks or disturbances. Patterns of organism distribution can be worked out from photos where scale, target distance, and angular field coverage are known or can be calculated.

Rock outcrops can usually be detected and delineated easily on photographs by means of contrast, resulting sharp boundaries, and relief with respect to the surrounding sediment.

Where ripple marks show up, it is safe to assume the presence of sandy materials, and of current or wave motion of sufficient strength to form the ripples. A knowledge of grain size and density, along with the velocity of water flow present, can be used to supplement the photographic data, furnishing descriptions of wave characteristics, estimations of length, and determinations of symmetry and steepness of ripple marks.

The firmness of the sediment-water interface can be determined indirectly from photographs. The generation of turbid clouds of fine-grained material by artificial agitation of the sea floor usually denotes a soft clay bottom. (On the other hand, such turbid clouds occasionally form over a hard bottom, the fine suspended material coming from elsewhere.) The presence of silt in clay hardens the bottom, and the effect is intensified when sand is present. Although these bottom materials are subject to movement

by water, the sediment-water interface is probably firm and sharply defined most of the time. The presence of coarse sand, gravel, pebbles, and boulders, of course, denotes a very hard bottom, capable of sustaining heavy underwater loads. Such bottom materials are usually easily determinable by photographic sampling. The freshness of the upper surfaces of manganese nodules, capping of sediment, banking of sediment, etc., give clues to the rate of sediment accumulation. Changes in bottom materials, outcrops, and chemical deposits can be studied photographically by tracing sediment boundary lines.

Repetition of patterns of sea floor features assists in extending the results of photo interpretation to other areas. Photographs can be compared on a geographic basis, by targets, by animal populations, or by microrelief types.

DISCUSSION OF THE ORIGIN AND OCCURRENCE OF MICRORELIEF

General

The sea floor can be described as a huge jigsaw puzzle. Much remains to be done before all the pieces of information concerning the individual phenomena that contribute to the formation of the microrelief can be fitted into a single, overall pattern. Nevertheless, some general statements can be made with respect to the origin, distribution, and relationships of the microstructures.

Thus, examination of surfaces and smaller related parts of larger underwater features has shown that the same kind of environment may extend for great distances. For example, Mero[16] states that sea floor sediments tend to be rather uniform over large regions and that a few chemical analyses of nodules can be averaged to give fairly reliable results. Averages of heights for visible targets distinguished in the photographic study described in this report are shown in figure 7. A specific area of the

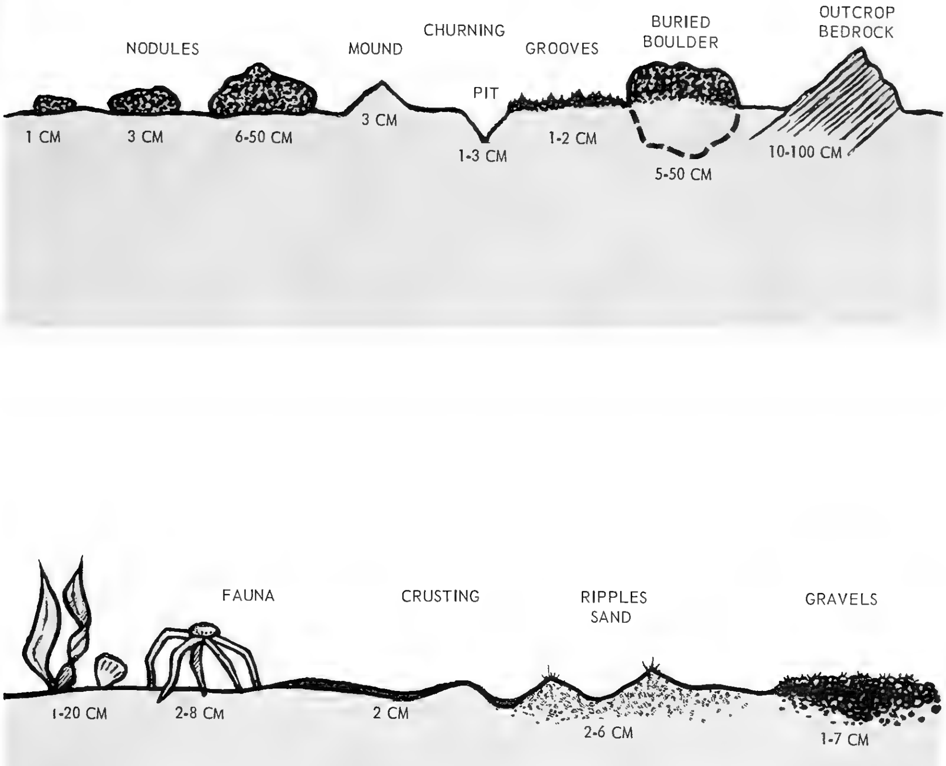
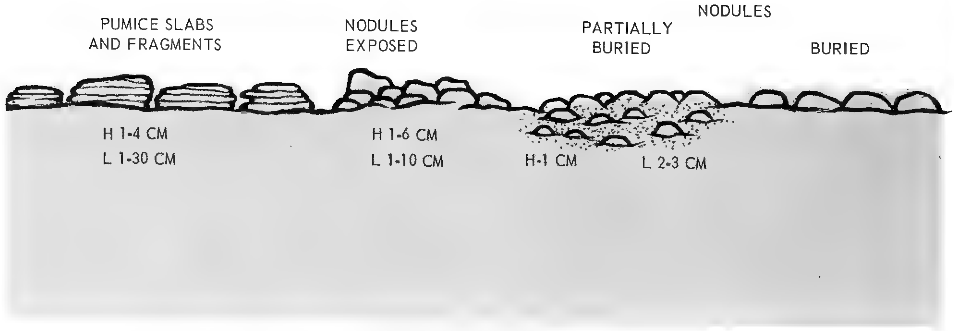


Figure 7. Microrelief on sea floor.

Pacific Ocean, the East Equatorial Province, was examined separately, giving the results shown in figure 8. Comparison of the two figures reveals that the very small relief is rather uniform over large areas.



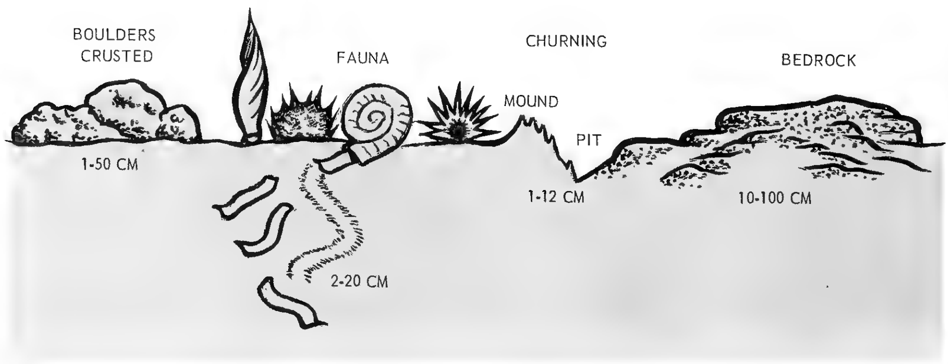


Figure 8. Microrelief on sea floor — east equatorial Pacific.

The NEL photographs have revealed similar environmental relationships in microrelief separated by hundreds of miles. Comparable microstructures also exist at different depths, presumably due to a depth-range toleration by many benthonic organisms.

Random sampling of irregularly distributed bottom targets makes it difficult to obtain accurate distribution counts. The photos revealed a range of distribution of small visible targets for all environments from less than 1 per square meter of sea floor to 5 or more. Tracks, markings, scratches, plow trails, impressions, pits, and mounds resulting from benthonic sediment churning did not vary greatly in magnitude and horizontal distribution considering the vast size of the oceans.

In shoal depths, organisms are normally plentiful because of rich food supplies. With greater depth there appears to be a linear decrease of the number of visible organisms, with a corresponding decrease of food. As an example of the numbers of organisms, Beagles and Shumway[17] reported high concentrations of clams ($400/m^2$) in depths of 5 meters or less in Alaska waters. Worm mounds up to 5 cm high in the same area indicated concentrations up to 10 animals/m^2. In other nearshore shallow areas in Alaska, Beagles and Shumway reported concentrations of worm mounds at $20/m^2$. On the other hand, many photographs taken in deep abyssal areas indicate benthonic organism populations of less than $1/m^2$. Number of benthonic fauna and amount of churning of sea floor sediments are closely related, as is to be expected.

There does not appear to be a close relationship between bedrock outcrops and manganese nodule formation, but further investigation will probably show considerable manganese encrustation on the harder surfaces such as bedrock and coral boulders that exist on topographic highs. Table 2 indicates a distinct relationship between physical disturbances such as wave or current-formed ripple marks and outcrops of rock. Photographs have repeatedly shown that coarser sediments such as *Globigerina* ooze and coral sands are rippled in the vicinity of bedrock.

Sediment and its Formation

The materials that constitute the sea floor are derived from various sources. Organic and inorganic matter falls from the water column or moves in laterally to find places of accumulation. Most inorganic matter comes from the erosion of subaerial rocks; from atmospheric fallout including dust, ash, and meteoritic spherules; and from volcanic activity. Ice rafting drops variable amounts of inorganic and organic material in the high latitudes, but in tropical and midlatitudes the quantity is not significant. Most organic matter comes from the tests and debris of organisms living in the upper layers of the oceans. Deep-water pelagic fish supply a varying amount of organic material to bottom sediments.

Turbidity flows help to move sediments rapidly into deep water toward their final resting places.[18]

Normally, in deeper water, the organic content of sediments is highly variable. Sediments, if rich in organic matter, support large colonies of surface and subsurface feeders leading, in turn, to churning and the development of microrelief. Where little organic material is present, churning is insignificant, microrelief is minimal, and the bottom approaches flatness. Nearshore sediments are made up largely of subaerial runoff, are usually extremely rich in organic matter, and form maximum microrelief.

Sediments are usually characterized according to their composition. If 30 percent or more is calcium carbonate, the sediment is designated a calcareous ooze. If less than 30 percent carbonate is present, the sediment is called a clay. When the sediment consists mostly of silica, it is designated a siliceous ooze.

In spite of wide differences in environment and origin, bottom sediments may still be acoustically similar as far as their microrough upper surfaces are concerned. Differences in color have no influence on sound reflection. Organic content of sediments may have some effect, but this has not been determined.

Rock Outcrops

Soundings, dredge samples, rock-damaged core barrels, and photographs have proved the existence of hard rock and other hard surfaces on the sea floor even in deep water. Acoustic probing has verified the occurrence of isolated pinnacles, lava flows, flat-lying buried strata, and partially covered boulders and loose rock at, or not far below, the sediment-water interface. The presence of exposed rock is related to major earth movements, erosion, volcanic activity, changing rates of sediment accumulation, bottom current, and wave action, and it also depends on the major underwater topographic features and superimposed intermediate relief. Usually, rock appears on ledges, ridges, topographic highs, and upper surfaces of seamounts; in trenches, canyons, fault scarps, and rift mountains; and on nearshore shelves, banks, and terraces. But it is probable that outcroppings of nearly all magnitudes occur throughout the entire range of underwater environments.

Rock relief above existing sediment surfaces varies in height from a few centimeters to thousands of meters. Although still within the definition of microrelief, many outcroppings examined photographically were more than 50 cm high. Partially buried boulders can appear as outcrops in bottom photographs, but probably are not continuous for any distance. Distribution of rock outcrop is highly irregular. Laughton[11] found that surface features of seamounts varied considerably over short distances. On a topographic high in the Indian Ocean, the surface at one location changes from cross-rippled sands to a manganese-encrusted bed of nodules or bedrock in a distance of not over 70 meters (fig. 9). Many small isolated local outcrops of a few meters in extent exist in a variety of surrounding areas of different origins. They are in sharp contrast to great underwater mountain ranges many kilometers in length. Depth of water is not a limiting factor.

Unless turbidity flows are active in an area, currents, wave and eddy action, and gravity pull tend to remove the finer-grained materials from isolated highs by a constant washing action.[19] It is not unusual for these agencies to keep areas clean of fine sediment cover for intermittent

lengths of time. In some instances remnant outcrops on abyssal plains are being kept free from fine sediments (fig. 10).

Gradually, the hollows, basins, lows, depressions, valleys, and other such areas along continental margins and in ocean deeps will fill up with sediment. The end result will be a smooth level plain, with the outcrops covered up.[20,21] Marine-cut rock terraces have formed in the past along the Southern California coastline and then have been buried with subaerial deposits.[21] Fortunately, both exposed and buried bedrock can be investigated with the subbottom acoustic profiler.

Seldom is it possible to detect freshly broken boulders or rocks on the sea floor. Exposure underwater eventually leads to crusting, and the process appears to go on endlessly.[1]

Manganese-encrusted bedrock, boulders, or nodules above the sediment surface indicate ineffective sediment accumulation for the area (fig. 11), and suggest that volcanism has been locally active.[22] In shallow areas of the lighted zone, organisms and plants attach themselves to hard surfaces forming colonies in a very short time (fig. 12). Busby[23] has discovered underwater outcrops of limestone in the Bahamas exhibiting microrelief features (cavities) that were formed subaerially and then submerged without appreciable change. Except in rare instances, rock outcrops tend to retain their original edges and faces. Unlike the rapid changes caused by subaerial erosion agents, changes to underwater rock occur very slowly unless the rock is exposed to earthquake and volcanic activity.

Figure 9. Manganese-encrusted bedrock, boulders, or nodules on a topographic high, Rift Mountains, Indian Ocean. Depth: 2940 m. Photo area: 0.6 m x 4 m. Type II camera. 2.4 m target distance.

Figure 10. Exposed bedrock enclosed by coarse, rippled calcareous sand on abyssal plain south of Java Trench, Indian Ocean. Depth: 3290 m. Photo area: 1.2 m x 3.7 m. Type II camera. 2.6 m target distance.

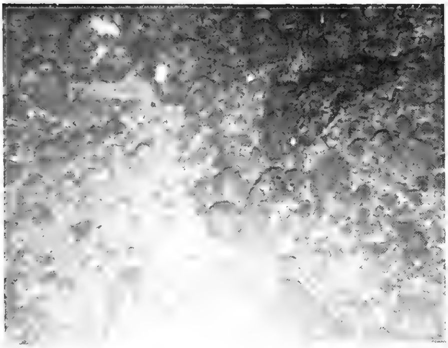


Figure 11. Manganese-encrusted boulders in coarse sand and gravel, located on ridge above elongated basin, Gulf of California. Depth: 720 m. Photo area: 1.2 m x 1.8 m. Type I camera. 2.4 m target distance.

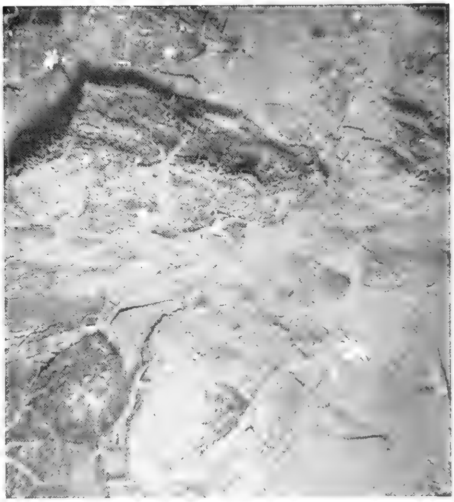


Figure 12. Exposed boulders imbedded in thin silty-sediment cover on upper flanks of Coronado Bank. Depth: 495 m. Photo area: 1.2 m x 1.8 m. Type I camera. 2.4 m target distance.

Microrelief Resulting from Physical Processes

Major processes, other than biological, responsible for the formation and disruption of microstructures on and within the sea floor are gravitational downslope movements, waterwaves and currents, and turbidity flows. The magnitude of these forces is attested to by an ever-growing library of bottom photos showing wave- and current-derived ripple marks in sandy sediments (fig. 13), grain sorting (fig. 14), gravel beds or lag deposits (fig. 11), scour around bottom objects (fig. 10), slumping on unstable slopes (fig. 15), and current-distorted benthonic animals. Even weather factors including surface winds have an effect. The author[24] has described the formation of cross ripples by the action of currents on submerged seamounts when underwater obstructions are present (fig. 14). Menard[25] regarded internal waves as a possible source of oscillations in deep water. Inman[26] pointed out that symmetrical ripple marks require oscillatory currents for formation. Busby[27] considered that, at a depth of 1929 meters in the Tongue of the Ocean, Bahamas, ripples were probably caused by tidal oscillations rather than by internal waves. Laughton[11] stated that, in the light of our present knowledge of deep currents, it may be possible to explain the formation of deep ripple marks in terms of steady currents. Further, variations in the symmetry of the ripples may be ascribed to local current and tidal fluctuations, rather than to short-period oscillatory motion of the water. Deep-seated tidal-wave motion plays an important part in the movement and formation of sediments.[19]

An increasing amount of information as to its effects on bottom sedimentation indicates the importance of turbidity flow. The irregular and heterogeneous sediment surfaces often attributed to turbidity flow are difficult to detect in bottom photos, and physical and biological processes tend to modify near-surface microstructures in a short period of time anyway.

Biological activity, especially burrowing on unstable slopes, could initiate and accelerate turbidity flows and resultant slumping and disruption of microstructures. Marks, pits, mounds, grooves, scratches, and impressions are short-lived and ever-changing. The bottom surfaces

Figure 13. Cross rippling in sorted calcareous sand on a topographic high, Rift Mountains, Indian Ocean. Depth: 2940 m. Photo area: 0.6 m x 4 m. Type II camera. 2.4 m target distance.

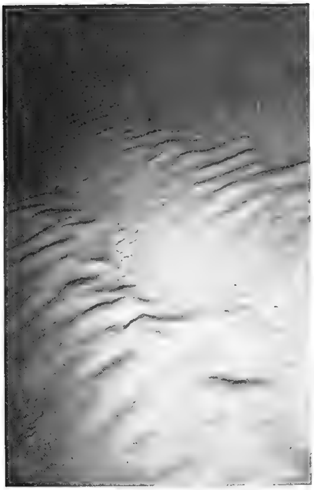


Figure 14. Cross rippling in sorted calcareous sand on a topographic high, Rift Mountains, Indian Ocean. Depth: 2940 m. Photo area: 0.6 m x 4 m. Type II camera. 2.4 m target distance. This photograph was taken a short distance from the one shown as figure 10.

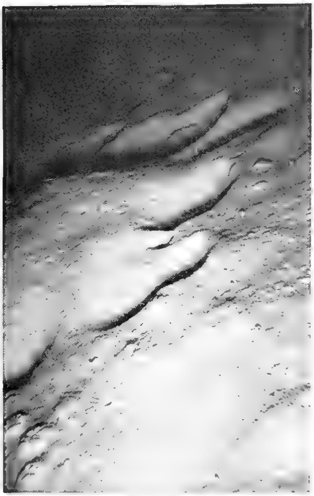


Figure 15. Sediment slumping in calcareous clay on slope of intermountain valley, Rift Mountains, Indian Ocean. Note sutured mounds and radial feeding pattern. Depth: 1760 m. Photo area: 0.6 m x 4 m. Type II camera. 2.4 m target distance.

involved tend to be soft and cohesive. Many abyssal deep-sea clay areas exhibit such softness, while other compacted and stable clay bottoms act as strong sound-reflecting surfaces. In some cases, subsurface reflecting surfaces are so hard that soft sediments at the water interface are masked out and become unrecognizable on sonic recorders. It would be difficult to measure the disruption that goes on during sediment accumulation before final consolidation takes place. The sediment surfaces exhibit some form and degree of microrelief throughout the period during which these processes occur.

The height of the microrelief caused by physical forces can be measured. Its extent can only be estimated from area to area, being beyond normal photographic limits. Laughton[11] has reported a wide range extending from ripples with wavelengths of a few centimeters to huge sand waves with wavelengths of a kilometer or more. Within photographic limits many ripple marks of symmetrical and asymmetrical shapes have been observed and recorded (fig. 16). The author[24] has reported wavelengths from 15 cm to 61 cm in calcareous sands on a submerged seamount surface at Eniwetok; ripple heights ranged from <2.5 cm to 15 cm. Vertical heights, averaged for the ripple marks noted in table 1 of this report, are between 2 and 6 cm (fig. 16).

Average values, of course, are of little use when analyzing the ripples on the sea floor because of the close relationship between type of microrelief and the intermediate or major feature on which it is superimposed. This does not mean, however, that every underwater topographic feature has its own kind of microrelief, since similar microreliefs exist in many different environments. Sand size, density, and chemical makeup, together with current or wave velocities, determine the ripple height and length. Variations in, or deflections to, the flow of water change or modify the shape and steepness of the ripple marks. As the velocity is increased, ripple mark formation continues until finally a high enough velocity is reached to destroy all the existing ripple marks. At such high velocities, grains move in sheet flow. Sand ripples normally form over a velocity range of 12 cm/sec in fine sand to 100 cm/sec in coarse granules.

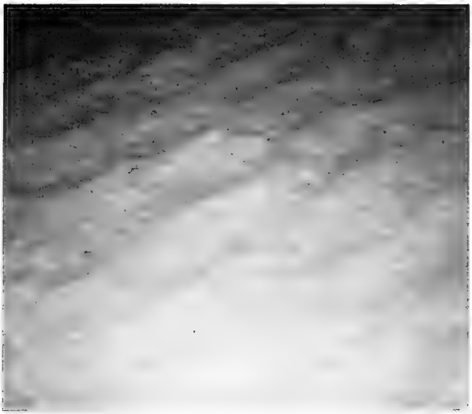


Figure 16. Manganese-encrusted symmetrical ripple marks in calcareous sand on southwest slope of Eniwetok Atoll. Depth: 1650 m. Photo area: 1.2 m x 1.8 m. Type I camera. 2.4 m target distance.

Deep-sea ripple marks show as great a variety of forms as those in shallow water. Variations in wavelength, crest length, amplitude, and symmetry occur over very short distances.[11]

Lack of ripple marks does not necessarily mean a lack of water motion; it could mean merely an absence of grains capable of being rippled by the moving water. Fine-grained silts and clays in abyssal deeps will not ripple regardless of the strength of the current. But scour marks can result, providing evidence of currents in such areas. Dzulynski and Sanders[28] hold that such marks are the result of scour of a cohesive mud bottom (clay) by turbulent eddies of sediment-laden water, and also that current marks can be made in any depositional environment where sand is transported over a cohesive mud bottom. These authors also consider that "tool" marks result from tractional movement of larger particles. Where the latter are lacking

and no sand grains are present, visible animal markings and impressions indicate a lack of current activity.

Currents are normally very small in deeper clay areas, but occasional banking of fine-grained sediments against nodules and rock outcrops indicates the presence of low-order water motion. Sometimes the bending of bottom-attached organisms and deformed bottom crawlers indicate weak sea floor currents.

Current meters attached to camera frames are now being used to measure water velocities at the sea floor in various environments.

Microrelief Resulting from Chemical Precipitation

Of all the microstructures that have been discovered on the sea floor, the manganese nodule, slab, or encrustation is perhaps the most interesting. It may have influence on sound reflectivity when concentrated, and it will probably have economic value to man in the future.

The manganese nodule, like phosphorite and ferric nodules, is a product of chemical precipitation that takes place at the sea floor (figs. 17 and 18). The manganese nodule usually contains small percentages of iron, cobalt, copper, and nickel oxides. Goldberg and Arrhenius[29] believe that organisms concentrate dissolved chemicals in the sea water column, after which chemical changes and attachment to various nuclei on the bottom occur. These authors have also suggested that there is a direct correlation between the iron/manganese ratio in nodules and the rate of sedimentation. Graham[30] believes that organic reactions in seawater form manganese nodules. Although the mode of formation of the nodules is not yet clear to the oceanographer, the deposits are substantial and form recognizable relief.

The heights and lengths of the nodules range from less than 1 mm to 50 cm or greater, but the nodules for a particular area usually fall within a narrow size range. The concentration (number of nodules per square meter of bottom) is difficult to determine. Sonar and TV scanning

promise to help solve this problem in the future. Sampling and extensive photography have disclosed the presence of different grades of manganese nodules over great areas, especially in the Pacific Ocean.[1] The distribution of the nodules is somewhat patchy which is to be expected in view of depth variations and the obstructing effect of major and intermediate underwater topographic features. However, regional patterns of surface nodules and encrustations do occur.[1,31]

Menard has concluded from photographs and dredge hauls that almost all rock outcrops in the open ocean are covered with oxides.[1] Slabs of volcanic ash or consolidated sediment encrusted with ferromanganese oxides (fig. 19) are very common in the eastern Pacific.[32]

Manganese nodules occur in a wide variety of underwater environments (table 1). In protected basins where water circulation is poor, nodules do not usually form. In fact it is not uncommon to find oxygen-starved sediments which form a reducing environment. Evidence of chemical reduction in sediments has been found in San Pedro Basin on the southern California Continental Terrace. The surface was mottled and smooth, and animal activity was lacking. Microrelief is very low in such areas because of the lack of organisms and of sediment-churning. Nodules are normally found on ridges, highs, hills, large mounds, in open deep-sea basins, and on abyssal plains (fig. 20) where oxygen is in plentiful supply, unless a very high sill cuts off water circulation. In some abyssal areas, nodules occur on highs and in lows between hills as a relatively uniform cover, but it is likely that most nodules are on hills.[1] Sediment accumulation would normally be greater in the lows than on the highs.

Cores from Pacific areas indicate that fewer nodules exist below the interface than at the interface.[1] To explain the presence of nodules at the surface, the sediment must accumulate at a slower rate than manganese oxide, although some workers now feel that organisms can keep the nodules at the surface in their search for food.[1] The author doubts the effectiveness of this mechanism, except in areas where nodules are small and closely spaced (fig. 21), since many nodules would be too large for any benthonic organisms to move except downward by undercutting.

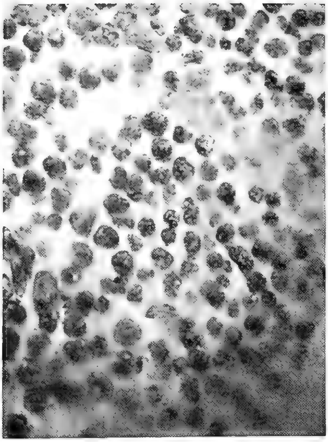


Figure 17. Free, spherical manganese nodules, 3.48 cm diameter, resting on Globigerina ooze. South central Pacific Ocean, northwest of Tahiti. Depth: 3695 m. Photo area: 0.5 m x 0.3 m Type II camera. < 1 m target distance.

Figure 18. Partially buried manganese nodules in clay sediment, Pacific Ocean south of New Zealand. Depth: 5160 m. Photo area: 1.2 m x 1.2 m. Type II camera. 2.6 m target distance.

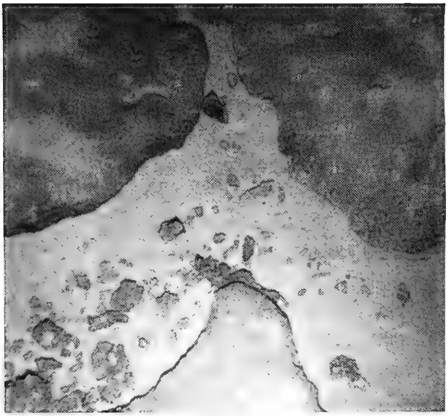
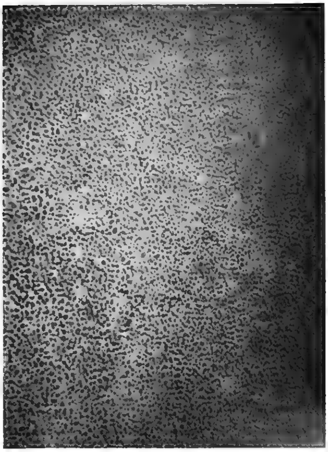


Figure 19. Manganese-impregnated pumice slabs resting on brown clay sediment; some clay capping is visible. East North Pacific. Depth: 4302 m. Photo area: 1.2 m x 1.8 m. Type I camera. 2.4 m target distance.

Figure 20. Scattered manganese nodules resting on red clay sediment, East Indian Ocean. Rough surface of clay indicates churning by benthonic organisms. Depth: 4940 m. Photo area: 1.2 m x 2.4 m. Type II camera. 3 m target distance.

Figure 21. A high concentration of evenly spaced spherical manganese nodules, 3.48 cm diameter, resting on a Globigerina ooze. Animal churning has caused the partial covering of some nodules. South central Pacific Ocean, northwest of Tahiti. The freshness of the nodule surfaces indicates a low rate of sedimentation in this area. Depth: 3695 m. Photo area: 1.2 m x 1.2 m. Type II camera. 2.6 m target distance.



A new approach to the problem of manganese nodule concentration at or near the sediment surface has been made by Olausson and Uusitlalo[33] who experimented with artificial sands. They contend that seismic vibrations may cause a lifting effect to keep large particles at the surface for longer times. This, they say, would give rise to high concentrations of nodules at the sediment-water interface and in regions with a comparatively high rate of sedimentation. However, this process would probably not be effective in cohesive clays. In some areas manganese nodules appear to be almost buried as a result of a high rate of sedimentation (fig. 18).

Type of manganese nodule varies from closely packed spheroids (fig. 21) to widely scattered irregular chunks (fig. 20) and encrusted, irregularly shaped, volcanic rock fragments. In places, manganese oxides have cemented sand surfaces, and closely packed nodules have coalesced to form hard rock surfaces (fig. 16).

Microrelief Caused by the Bodies of Benthonic Organisms

That organisms exist on the sea floor has, of course, been known for many years.[33-35] Strange looking creatures have been brought to the surface by dredge, trawl, sounding leads, nets, anchors, scoops, and other means in increasing numbers (figs. 22 through 27). Although many of these animals are alike in structure, they differ from species that live in shallow environments.

Because of the usual haphazard manner of collection and lack of detailed distribution information, little is known about these bottom feeders and burrowers. Sampling has been insufficient to establish the concentration of most of them. Exact identification from photographs, also, is difficult unless actual specimens are available for confirmation. However, increased use of bottom photography and coordinated sampling has somewhat alleviated these difficulties, and the concentration of a few identifiable animals has been obtained.[34]

Few underwater photos of the sea floor exceed 5 square meters in coverage. Most present-day samplers collect from areas of about 0.4 to 1 square meter of the sea floor. And single grabs seldom bring up more than one organism or part of an organism, although bottom trawls and dredges screen more sediment and yield more specimens.[35] Thus, few of the deep-sea animals are ever visible for counting and examination. And counting is complicated by the fact that some organisms combine bottom and subbottom feeding habits.

In most deep-sea environments the food supply is sufficient to support only a few animals, from less than one per square meter in fine-grained red clays to approximately ten in richer nearshore silts and clays. In abyssal plains and interseamount areas where intermediate relief is slight, the numbers are even smaller. Those animals living at the interface and visible in photographs vary in size from less than a millimeter to 15 centimeters in length (fig. 28).

To constitute effective microrelief on the sea floor, many organisms would have to be concentrated there. In large enough numbers, as in shallow water, crustaceans,

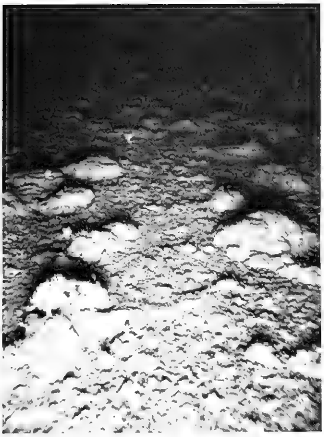


Figure 22. Coral growing on encrusted volcanic boulders, inshore slope on east side of Mauritius Island, Indian Ocean. Depth: 479 m. Photo area: 0.6 m x 4 m. Type II camera. 2.4 m target distance.

Figure 23. Holothurian (sea cucumber) and small ophiuroids (brittle stars) on surface of brown silty clay in San Diego Trough. Depth: 905 m. Photo area: 1.2 x 1.8 m. Type I camera. 2.4 m target distance.

Figure 24. Numerous worms protruding from churned silty clay on east slope of Guaymas Basin, Gulf of California. Depth: 610 m. Photo area: 0.6 m x 4 m. Type II camera. 2.4 m target distance.

Figure 25. Ophiuroids (brittle stars), holothurians (spiny sea cucumbers), on churned surface of brown silty clay in San Diego Trough. Depth: 905 m. Photo area: 1.2 x 1.8 m. Type I camera. 2.4 m target distance.

Figure 26. Sea pens growing on well churned clay in north Guaymas Basin, Gulf of California. Depth: 894 m. Photo area: 0.6 m x 4 m. Type II camera. 2.4 m target distance.

Figure 27. Large sea urchin on rippled gray sand, marine slope of Saint Paul Island, Indian Ocean. Depth: 448 m. Photo area: 0.6 m x 4 m. Type II camera. 2.4 m target distance.

Figure 28. Large ophiuroid (brittle star) and a number of small, spiny holothurians (sea cucumbers) on silty clay in protected Flores Sea basin north of Soembawa Island, Indonesia. Depth: 2094 m. Photo area: 0.7 m x 0.9 m. Type III camera. 1.5 m target distance.

starfish, brittle stars, sea cucumbers, sponges, crinoids, worms, and urchins might have sufficient density and height to constitute microstructures capable of reflecting sound or changing coefficients of sound reflection.

It may be concluded that, except in shallow areas, the bodies of living organisms themselves hardly affect the reflection of sound.

Microrelief Caused by the Activity of Benthonic Organisms

During feeding, benthonic organisms churn up the softer sediments of the sea floor.[11,13] Sokolova, working in the Kurile-Kamchatka Trench of the Pacific Ocean, found that most (about 55 percent) of deep-sea bottom invertebrates are deposit feeders, a smaller number (about 25 percent) are suspension feeders, and still fewer (about 20 percent) are carnivorous.[36] Further, the composition and quantitative abundance of deep-sea communities are largely determined by the amount of organic material on the sea floor and in suspension in the water layers just above the bottom. Sokolova adds that a zonation of communities arises, each zone extending over a region characterized by a distinct type of sedimentation. The dominant organisms in each area are those best adapted to it by their feeding habits.

Organisms living in the deep-sea environment must spend their entire lives seeking out and digesting food. Even where food is plentiful, for example, in nearshore areas fed by rich subaerial runoff, the organisms must spend most of their time seeking food.

Laughton[11] found more sediment disturbance and more animals in shallow water (fig. 26), and less disturbance and fewer animals in deep water (fig. 28). This relationship results from diminishing food supplies with increasing depth. Numerous bottom photographs on deep abyssal plains bear this out (fig. 29); here the main source of food is the surface water. If the latter is not rich in nutrients, as it seldom seems to be over abyssal areas of the midlatitudes, very little organic debris falls to the sea floor. Also, because of the great depth, a large percentage of the falling

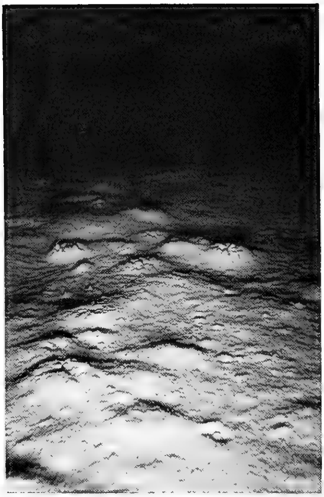


Figure 29. Sutured animal mounds, in churned red clay, intermountain valley of Rift Mountains, Indian Ocean. Depth: 1760 m. Photo area: 0.6 m x 4 m. Type II camera. 2.4 m target distance. The mounds are 5 cm high and probably created or altered by crustaceans.

debris is apt to be consumed by pelagic fishes before reaching the sea floor.

Benthonic organisms of the deep barren areas are therefore forced to crawl, burrow, plow, hold fast, and dig in the sediment for the minute quantities of food available (fig. 30). More churning, of course, takes place in the organically rich, shallow coastal sediments (fig. 31), because of the greater numbers and varieties of organisms present. In the process of seeking food, the organisms build undersurface galleries, tubes, and tunnels.

Regardless of the total amount of churning, the vertical height of the resulting microrelief seems to reach an equilibrium at 6 centimeters above the sediment-water interface. Benthonic organisms such as brittle stars, holothurians, starfish, urchins, and even crustaceans seem unable to build up larger microstructures and, indeed, have no need to do so since their only objective is to obtain food.

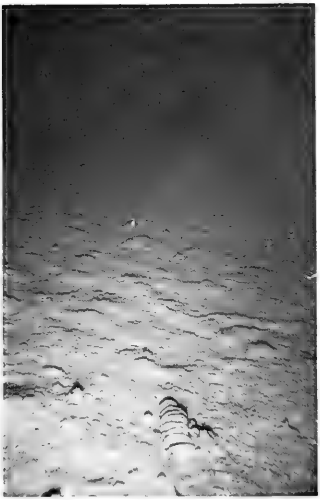


Figure 30. Worm and excrement on mottled clay near Cocos Keeling Island, Indian Ocean. Depth: 5100 m. Photo area: 0.6 m x 4 m. Type II camera. 2.4 m target distance. Mounds are 3 cm high.

Figure 31. Starfish, brittle star, and sea pen on churned silty clay, west slope of Guaymas Basin, Gulf of California. Depth: 911 m. Photo area: 0.6 m x 3 m. Type II camera. 2.4 m target distance. Pits are approximately 15 cm deep and 30 cm wide across the openings.

Burrowing organisms, whether they feed at the surface or just below it, digest enormous quantities of sediment. They produce ribbons of excrement (fig. 30) and tunnels that wind around in crisscrossing patterns, evidence of effective extraction of organic matter. The activities of these organisms must have an overall effect on the strength, shear properties, and reflectivity of sediments. Tunnels, voids, changes in porosity, and disruption of grain alignment individually may not be of great importance, but collectively they contribute significantly to the general pattern of the microrelief.

Summary of the Origin and Occurrence of Microrelief

The summarized information in this section is arranged to correspond with the five microrelief types of table 2.

I. ROCK OUTCROPS AND BURIED BOULDERS

These usually occur on shoaler and irregular underwater topographic features such as banks, island shelves, sides of troughs, seamounts, mountains, cliffs, ridges, canyons, marine terraces, and shelf breaks. Medium-to-coarse sands are usually present near the outcrops and show ripple marks, scour, banking, and other signs of water activity. Fine-grained materials other than fine-grained sands, such as silts and clays, have usually been washed into deeper water leaving the rock outcrops and gravel deposits exposed. A variety of benthonic organisms, together with a few fish, live in or near the shallow rocky environments, whereas finer sediments, manganese coatings and crusts, and infrequent benthonic organisms occur in the deeper rocky environments. Rock outcrops usually consist of volcanics (including basalt flows and pumice slabs), coral boulders, and conglomeratic aggregates, and they are normally coated with manganese and iron oxides.

II. CHEMICAL DISTURBANCES

Manganese nodules are the most prominent free chemical precipitate on the sea floor. They occur over a wide range of depths, but are most noticeable on topographical highs, on red clays below 5000 meters, and on shoaler calcareous oozes. They are present in high concentrations on extended abyssal areas and in deep-sea basins of all major oceans, constitute strong microrelief, and represent a mineral resource of great potential economic value. Phosphorite slabs are found in high concentrations on coastal banks where they are localized. Both manganese

and phosphorite deposits may have a strong acoustic reflecting effect since they occur at or near the sediment-water interface. How these concentrations arose is not not clearly understood at the present time.

III. BENTHONIC ORGANISMS

Organisms living on or near the sea floor surface are nearly always associated with soft, organically rich clays, and nearshore silts and clayey silts. If burrowing organisms such as worms and sea cucumbers are present, the bottom materials are apt to be churned or disrupted by feeding, exploratory, or escape activities. Surface feeders such as sea urchins, crustaceans, and brittle stars account for a large portion of the tracks, trails, scratches, and marks found on bottom sediments. Brittle stars and sea cucumbers engage in both burrowing and surface feeding activities. Other organisms such as corals, sponges, sea pens, and some worms hold fast to the bottom and filter-feed directly from the water. Crustaceans and brittle stars normally move about over many bottom environments seeking detrital particles and modifying microstructures such as mounds and pits formed by burrowing organisms.

Fewer species of animals, but often of larger size, are present in deeper environments where food is relatively scarce. Animals are normally abundant in shoaler nearshore areas where surface plankton blooms and subaerial runoff from adjacent land areas provide large quantities of organic matter. Benthonic organisms are not present in high enough concentrations in deeper waters to greatly affect directed sonar signals.

IV. CHURNING OF SEA FLOOR SEDIMENTS

The churning is related directly to the abundance of burrowing organisms and the quantity of food matter present; and it is most noticeable in clays and clayey silts, and in shallow water. Water depth is related to the degree of churning, amount of resultant microrelief, and the predominant type of microstructure present. Churning takes

place in all sediments inhabited by benthonic organisms. Sometimes it is localized, but normally it exists over great areas and often with very little variation from environment to environment.

V. PHYSICAL DISTURBANCES OF BOTTOM SEDIMENTS

Waves and currents, together with earthquake jarring, faulting, gravitational slumping, turbidity flows, and tsunamis, all affect the sediment-water interface. Study of the types, numbers, and distribution patterns of the marks left on the interface helps determine the origin, strength, and mode of operation of the physical forces involved. Normally, the latter are active in canyons, on seamounts, on topographic highs, on marine terraces, in channels, on beaches, and in coarse sediments around rocky outcrops.

Symmetrical ripple profiles denote oscillatory wave motion, whereas asymmetrical profiles are indicative of currents coming strongly from one general direction. Visible ripple marks are evidence of the water velocities mentioned in a previous section, above and below which sediment grains move only in sheet flow without rippling. Clays do not ripple at any velocity because of the coherency of the fine grains, but gravels can be rippled by strong currents under certain conditions. Many ripple marks have been preserved in place by the cementing of sand grains after rippling. Water motion, sand grain size, and chemical makeup, rather than depth, are the limiting factors in the formation of ripple marks. The water velocities needed to initiate rippling are directly proportional to the density of the sand grains. Coarse sediments are most often detected where rocky outcrops or boulders are exposed, that is, usually on shoaler topographical features.

A SEA FLOOR MICROROUGHNESS SCALE AND WORLDWIDE ZONES OF ISOROUGHNESS

Microrelief Numerical Ratings

Individual descriptions of sea floor microrelief, and predictions of its environmental distribution, have little practical value unless the results can be expressed quantitatively. In a numerical form, however, roughness of the sea floor can be correlated with other factors influencing the transmission of underwater sound, such as sediment properties, sound velocity, temperature, salinity, and larger topographic features.

An arbitrary scale of sea floor roughness has been developed from the measurements and photo-interpretations of table 1, and is presented here as table 3. In addition to numerical ratings, table 3 includes an explanation or definition of the meaning of each rating.

This numerical scale of sea floor microroughness is a beginning attempt, with a minimum of data, to provide a means of predicting microrelief for acoustic purposes. It is hoped that roughness ratings for all sea floor areas can eventually be obtained for use in both military and commercial applications. The success of this endeavor will depend on the accumulation of more and better data, and particularly on accurate ship positioning, camera control, and depth measurement.

A summary of microrelief characteristics follows which, it is hoped, will make the ratings more useful.

TABLE 3. NUMERICAL SCALE OF SEA FLOOR MICROROUGHNESS AND DESCRIPTIVE NOTES

	Numerical Rating of the Relief
Canyon – inner	5
Bank	4
Irregular topography	4
Small local ridge	4,3
Island slope	4,2
Local ridge	3,4

TABLE 3. (Continued)

	Numerical Rating of the Relief
Side slopes of trough	3
Low hills	3
Topographic high	3
Island shelf	3,2
Seamount surface	3,2
Irregular topography	3,2
Island slope	2,4
Seamount surface	2,3
Island shelf	2,3
Irregular topography	2,3
Basin	2
Canyon – outer	2
Continental slope	2
Sill	2
Valley	2
Rift valley	2
Gentle relief (275 meter hills)	2
Irregular hills (180 meter relief)	2
Intermountain valley	2
Abyssal hills	2
Gentle topography	2,1
Gentle topography	1,2
Saddle	1
Slope	1
Sea valley	1
Smooth topography	1
Flat topography	1

EXPLANATION OF NUMERICAL RATINGS

Because the sea floor is never perfectly flat, the rating zero is not used. The rating 1 denotes minimum but recognizable roughness; the rating 5 denotes maximum roughness. Some descriptive notes on the ratings follow:

1. Almost smooth surfaces formed on clays, oozes, and silty clays in abyssal areas between, and on, major and intermediate topographic features. Visible evidence of churning is lacking, with a minimum of epifauna and infauna present. Rock fragments and manganese nodules occur in scattered patches, varied according to chemical composition of water.

Height of churning 3 cm.
Normal range of microrelief 0 to 10 cm.

2. Low-order bottom relief formed by fauna churning on clays, oozes, and silty clays in areas of gentle relief. Such low-order relief also occurs on marine slopes, valleys, basins, and other gentle topographic features. More epifauna visibly present but not in great numbers in deeper areas. Occasional occurrences of small manganese nodules and rock fragments in tightly packed or scattered patterns of distribution, again dependent on seawater conditions. Occasional occurrences of loosely scattered and larger manganese nodules with visible churning between targets. Oozes are normally in shoaler areas and are coarser grained.

Height of churning 3 to 6 cm.
Normal range of microrelief 3 to 20 cm.

3. Maximum churning of clay and silty sediments. Ripple marks occur where fine sands and sandy silts are present. Greater occurrence of larger manganese nodules, pumice slabs, and rock fragments. Chemical crusting of sediments sometimes present. Major and intermediate features predominantly island slopes, hills, ridges, highs, and irregular topography.

Height of churning 6 to 15 cm.
Normal range of microrelief 6 to 30 cm.

4. Rock fragments, outcrops, boulders, and coarse sediments predominate in this shoaler environment. Fauna churning maximum where silty sediments exist. Ripple marks often present in sandy sediments. Greater abundance of epifauna on rocky surfaces.

Height of churning, where present, 15 cm.
Normal range of microrelief 6 cm to 1 meter.

5. Jagged rocks, phosphorite nodules, large boulders, and coarse sediments on upper surfaces and slopes of underwater features such as ridges, mountains, banks, cliffs, walls of canyons, and other topographic highs. Fauna churning of coarse sediments variable and dependent on presence of organic matter. Predominance of attached and unattached epifauna on rock exposures.

Height of churning highly variable up to 15 cm.
Normal range of microrelief 3 cm to 2 or 3 meters.

Summary of Microrelief Characteristics

1. In general, microroughness is directly related to the intermediate and major topographic relief on which it is superimposed.

2. With some exceptions, microrelief diminishes in magnitude with increasing depth. Outcrops are fewer in deeper water where less infauna and epifauna are present

to disrupt normal processes of erosion and sedimentation. Surfaces of targets are cleaned or smoothed by the fine-grained materials falling through the water column. Iso-microroughness values continue largely unchanged for hundreds of square miles.

3. Whatever its origin, the magnitude of the roughness eventually reaches an equilibrium value.

4. There are many causes of microrelief, but they are of less importance acoustically than an ability to delineate the shape or pattern of the relief for a particular environment at a specific time.

5. Microroughness in deeper water is largely caused by infauna churning in clays and silts where organic matter is scarce.

6. Microroughness in shoaler areas, in contrast, is influenced mainly by the presence of rock outcrops and the effects of epifauna attached to hard surfaces. Ripple marks are present because of the greater occurrence of sandy sediments. Churning is highly variable in nearshore sediments because of the great influence of inflowing subaerial sediments, light, and plant life. The acoustic effects of nearshore sediment roughness are predictable. Sediment changes occur faster than in deeper water.

Microrelief Interrelationships and Distribution

Figures 32A through 32E have been prepared as an aid to the study of the origin and distribution of microrelief, and the interrelationships of different types of microrelief.

Figure 32A shows the distribution of sea floor roughness according to the numerical scale of table 3, and general zones of isoroughness. Figures 32B through 32E similarly show the distribution of ripple marks and bedrock, manganese nodules, benthonic organisms, and biological churning, respectively. A close relationship naturally exists between figures 32D and 32E. Exposure

A

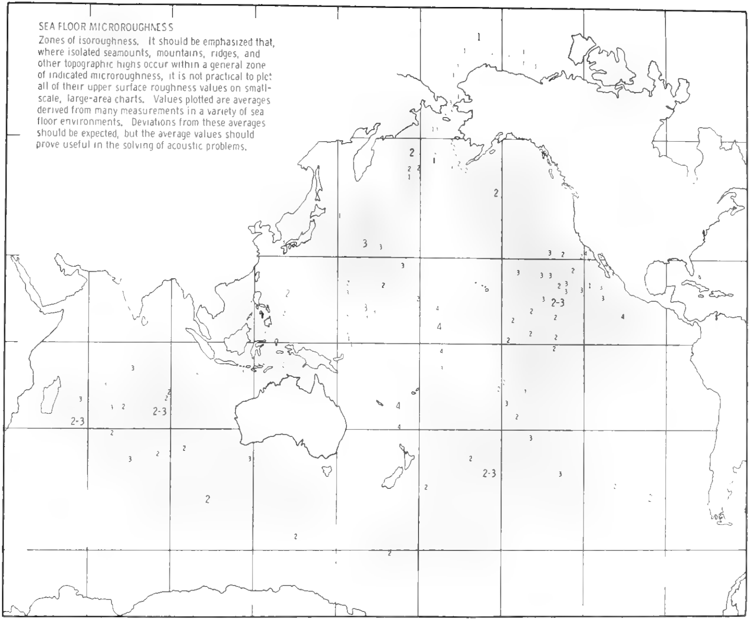


Figure 32. World maps showing NEL sea floor camera stations and underwater topographic features (continued through page 61).

B

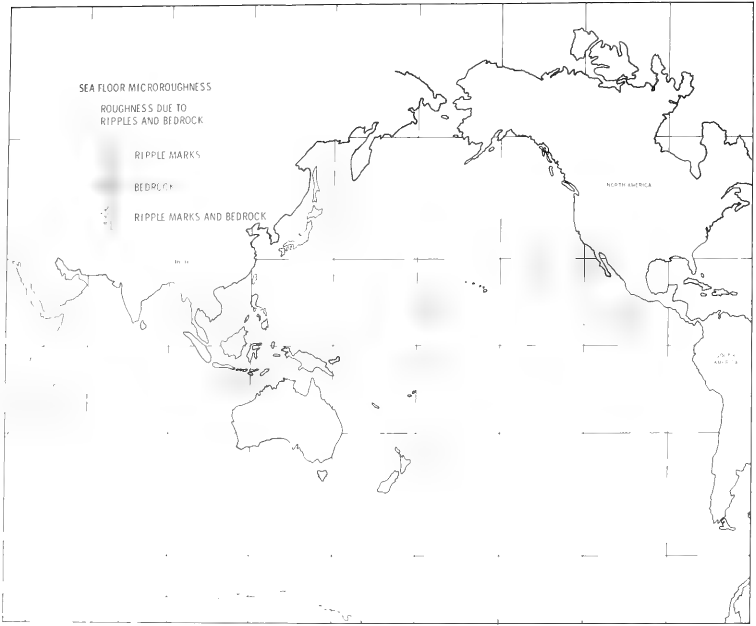


Figure 32 (Continued)

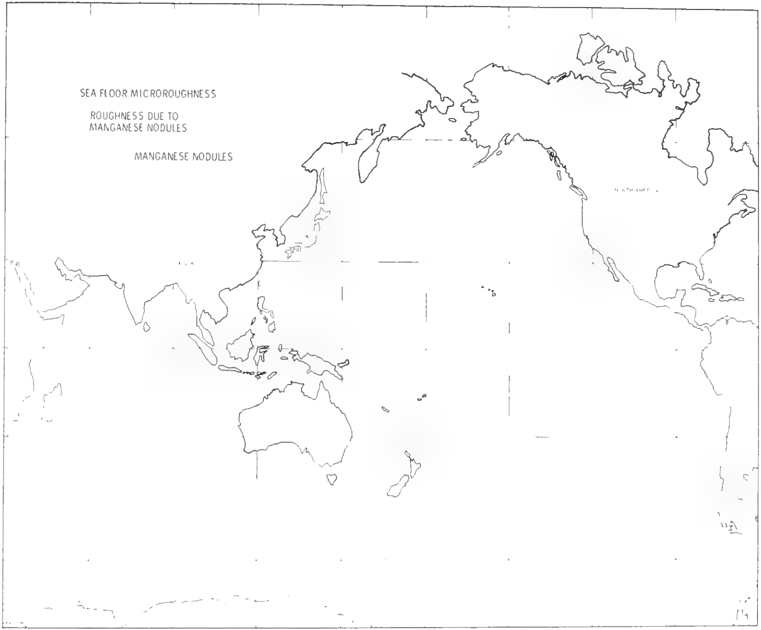


Figure 32 (Continued)

D

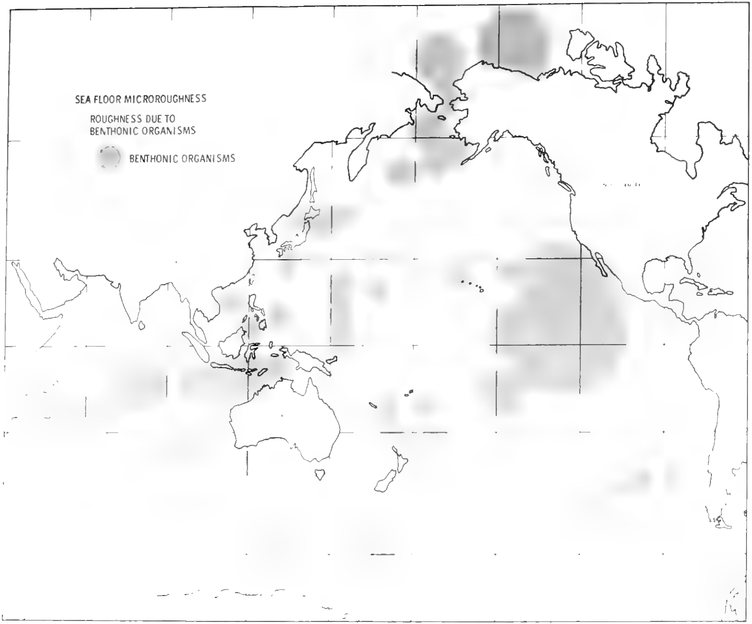


Figure 32 (Continued)

E

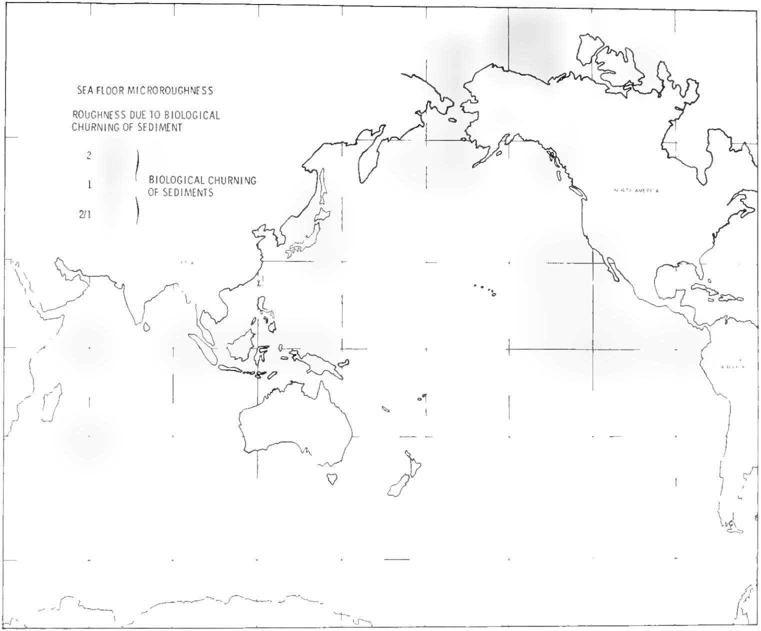


Figure 32 (Continued)

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of bedrock (fig. 32B) normally means the presence of coarse sediments and bottom currents, with ripple marks often resulting. The great areal extent of manganese nodules (fig. 32C) in both the Indian and Pacific Oceans requires that this type of microrelief be studied for its possible influence on underwater sound transmission. (A chart showing the distribution of manganese nodules at the sediment-water interface is now in preparation. Source information includes photographs, samples, dredge hauls, and foreign and domestic scientific reports.)

When studied together these figures should permit microrelief interrelationships to be established. The value of such a series of figures will grow with the accumulation of microrelief data. It is believed that the correlation of type of microrelief with depth on specially constructed bathymetric charts will permit a more accurate numerical zoning of roughness and point up the effect of roughness on the bottom reflection of sound.

Zones of Isoroughness

The general zones of isoroughness delineated in figure 32A should be accepted with caution until much more photographic sampling of the oceans has been performed. At present there are many gaps in the data.

The Gulf of Alaska and the area southward to just north of the Mendocino Escarpment is largely an abyssal plain with many isolated seamounts. No camera stations have been occupied in this great area but, on the basis of studies in other abyssal plain areas, a roughness rating of 2 has been assigned to it. The East Pacific Fracture Zone and Baja Seamount Province constitute a fairly large area of generally irregular topography. Roughness rating here will vary from 2 to 3, and reach 4 in some coastal areas where there is a high percentage of bedrock outcroppings. The sediments in the southwestern Pacific Basin are largely of pelagic origin. Red clays predominate but grade into coarser calcareous oozes on the flanks. Microroughness rating varies between 2 and 3 because of the presence of manganese nodules in the deeper areas. Most of the semi-closed deep-sea basins in the Pacific Ocean are largely

supplied by pelagic materials from the water column, but they do not all have free manganese nodules present on their deeper floors. The Philippine Basin floor is marked by a series of low abyssal hills with red clays predominating. The South Australian Basin has a smooth red clay bottom with numerous scattered nodules. Microroughness rating will vary from 1 to 2 in most of these basins. The large abyssal area lying southwest of the Emperor Seamount Chain and north of the Marcus Necker Ridge is largely made up of abyssal aprons and has a roughness rating of 3 due to the presence of manganese nodules.

North of the Bering Straits and on into the Beaufort Basin, the bottom relief is of very low order. Smooth surfaces and minimum churning keep the roughness rating to 1. In the Gulf of California, the rating is high in the canyon and ridge areas but drops to 2 in the deeper basin areas. The Indian Ocean is roughly divided into a western shallow part of calcareous ooze and a deeper eastern part predominantly red clay. A median ridge trending northwest-southeast appears to be the dividing line. However, roughness rating varies from 2 to 3 over most of the Indian Ocean because of the presence of manganese nodules and irregular bottom topography. The roughness rating in the Indian Antarctic Ridge area drops to 2. Nodules are not present, and churning is not pronounced; numerous tracks and trails indicate a paucity of organic matter. Very few identifiable animals are present at the interface.

CONCLUSIONS

Microrelief is related to, and directly influenced by, volcanism, earthquakes, mass water movements, depth of water, chemistry of seawater, sediment accumulation, turbidity flows, atmospheric fallout, subaerial runoff, biological activities, geographical location, and intermediate and major underwater relief features. Microrelief is not confined to visible microstructures at the interface but also occurs as subsurface internal structures of varied origin. The importance of microrelief is only now being recognized because of its effect on underwater sound transmission.

Microrelief will have a bearing on the future construction of underwater launching pads, roads, industrial plants, towers, transducer platforms, dwellings, and farming areas, as well as on methods of waste disposal and on the underwater movements of submersibles and tracked vehicles.

Patterns of microrelief over thousands of square miles of sea floor are being recognized. From many photographic samplings and target measurements, a numerical scale of sea floor microroughness has been established that should prove useful for acoustic purposes.

Zones of equal sea floor roughness and general similarities have been delineated in parts of the Pacific, Indian, and Arctic Oceans. Because of the existence of multitudes of localized smaller features, it is impossible to show microrelief in its entirety on the small-scale charts normally employed. The average values that are shown should, however, permit predictions to be made to assist in the solving of acoustic problems.*

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* Stereophotographic studies of sea floor roughness now in progress will provide greater resolution of microslopes.

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Over 700 NEL sea floor photographs, obtained intermittently over a 10-year period, in a wide variety of environments, have been analyzed. Five major types of bottom microrelief, on the basis of origin, have been defined; a numerical scale of microroughness has been developed and ratings predicted for normal bottom environments; and zones of isoroughness have been delineated for large portions of the Pacific and adjacent ocean areas.

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1. Ocean Bottom - Photographic Analysis

I. Shipek, C. J.

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